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Sensitivity of silage-maize to climate change in Denmark: A productivity analysis using impact response surface

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ABSTRACT

The sensitivity of silage maize to changing climate in Denmark under varying Nitrogen (N) and undersown catch crop (CC) treatments was investigated using a process-based, soil-plant-atmosphere model; Farm Assesment Tool (FASSET), and the impact response surfaces (IRS). The baseline period consisted of an experiment over a 3-year time period from 2009 to 2011 that was carried out in mid Jutland, Denmark (56°5′N, 9°56′E 38 m asl). The results indicated that an increase from the average annual temperature (≈6.5 °C) of up to 1.5 °C is beneficial for maize yield. At approximately 8 °C annual average temperature and above, the yield dropped sharply, and any positive impact of varying N treatments and CC was diminished. The maize yield was not as sensitive to precipitation as it was to temperature. The undersown grass in silage maize was not found to be a viable option in relation to warmer climate for all of its benefits were widely overshadowed by the excessive NO_3^- leaching risk. This study suggested that the warming of the climate along with the projected increase in precipitation in Denmark in the future will greatly challenge the management of N in maize cropping systems. Under changing climate, increasing crop N uptake efficiency by both maize and CC should be targeted as priority. Root growth in this context is an essential feature for the N uptake efficiency. Further research on potential adaptation of different deep-rooted species in the warmer climate that might be suitable as undersown CC is needed.

1. Introduction

The changes in climatic conditions are altering the crop cultivation practices in many areas. In Europe, an increase of about 0.9 °C in temperature has been experienced since the early 1900 s. The warming rate was between 0.13 and 0.24 °C per decade for 20-year periods since 1976, and the ten warmest years throughout the recording period have occurred since 2000 (Parry et al., 2007). In Northern Europe specifically, seasonal variations in temperature and precipitation patterns now allow grain maize production in Lithuania and Southern Sweden, and forage maize in Denmark, Estonia, Latvia and Norway (FAO, 2015). The shifting in maize cultivation areas towards the north are projected to continue into the future (Fronzek and Carter, 2007). Given the expanding cultivation areas and insufficient knowledge on maize production in Northern Europe, further research regarding the maize response to changing climate in Northern Europe is needed. Specifically, the response of crop growth, and the differential response between mono-crop and catch-crop systems, or varying levels of N fertilization effects are much sought for.

While maize has high N uptake potential, it is associated with highly fluctuating levels of soil mineral N after harvest (Hansen and Eriksen, 2016). N processes are inevitably affected by the increased temperature, and increased or decreased soil moisture. Christensen and Christensen (2007) suggested that the annual mean temperature in Scandinavia will increase by as much as 4.16 °C, and the precipitation by 9% by 2080. Under these conditions, the mineralization rate of N in crop residues and soil organic matter was expected to increase in Denmark (Olesen et al., 2004), potentially leading to significant amount of N losses through leaching especially in sandy soils (Askegaard et al., 2011). In maize cultivation, the amount and timing of fertilizer N applications, grass as an under sown cover crop, and N dynamics are therefore receiving increasing attention. While the studies highlight the complexity of intercropping and its effects on soil N dynamics even at a local scale (Hansen et al., 2000; Buchter et al., 2003; Hansen and Eriksen, 2009; Manevski et al., 2015; Hansen and Eriksen, 2016), the complexity further increases when accounting for the potential effects of climate change (Patil et al., 2010).

With a goal of analyzing the sensitivity of maize to wide range changes in temperature and precipitation, we present a detailed maize crop response analysis to climate change, in which the effects of

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different fertilization strategies and CC were taken into account. The current study was designed to show a spectrum of simulated responses to climate change of one year (2010) of an experiment that was carried out between 2009 and 2011. This was achieved using the IRS approach. IRS allows presenting the response of a state variable to two or more independent variables. The main principle behind the IRS is to help optimize the use of resources by designing experiments (Box and Wilson, 1951). Because it is used determining the optimal value of the independent variables that produces a maximum or minimum response, IRS can be adopted to investigate the response of the crops to climate change. As such, this approach had been introduced in the investigation of crop yield response (e.g. Pirttioja et al., 2015), crop production potential under climate change (Van Minnen et al., 2000), and the optimization of resource use in crop production (Koocheki et al., 2014). In this study, we investigated the sensitivity of the silage maize to climate change in Denmark under varying N fertilization and CC treatments.

2. Materials and methods

2.1. Study area

The experiment site is located in Foulum, mid Jutland, Denmark (56°5′N, 9°56′E 38 m asl), where the landscape is flat and the soil is of sandy loam glacial tills from the Weichsel glaciation (Breuning-Madsen and Jensen, 1996). The soil is free draining and consists of 8% clay, 11% silt and 79% sand at the top 25 cm level with bulk density of 1.54, and organic carbon content of 2.4%.

The climate in the study area is temperate with winter (December - January) mean temperature around 0 °C and summer (June-August) mean of 17 °C. The average annual precipitation is approximately 715 mm. The annual potential evapotranspiration (PET) is approximately 550 mm, and the actual is approximately 380 mm. PET exceeds precipitation in spring and early summer, leading to depletion of soil water. In late autumn, winter and early spring, 150–400 mm water leaches through the soil. Due to precipitation surplus in late autumn, soil water reserves are replenished (Cappelen, 2012).

2.2. Experimental design and, treatments

The experiments were carried out in a three-year period from 2009 to 2011 on randomized split-split plots (9 × 12 m) with three replicates. The main plot treatment was the 10-year cropping history (1999–2008) of either continuous silage maize or grass-clover mixture intermittently undersown to spring barley. For the current study, we used the cropping system that consisted of continuous silage maize (with spring rape sown only in 2004). The experiments had two subplot treatments that were used in this study. The first was the N fertilization rates at prescribed by standard rate for maize (Plantedirektoratet, 2013) at approximately 160 kg N ha^{-1}, 50% below, and 50% above recommended levels. From here onward the N rates are denoted as N, 0.5 N, and 1.5 N. For N treatments, a combination of mineral and organic forms was applied (Table 1). The N was applied in April each year with two to five days of difference between the application of organic and mineral form. The second subplot treatment was the use of CC.

Table 1
Annual amount and type of N input during the 10-year cropping history and the actual experimental period between 2009 and 2011.

10-year cropping history	Actual experiments (2009 – 2011)						
Mineral/Organic N ratio	Year	Mineral (kg N ha^{-1})			Organic (kg N ha^{-1})		
		0.5 N	1 N	1.5 N	0.5 N	1 N	1.5 N
142/32	2009	20	20	80	86	184	184
	2010	20	20	80	85	170	170
	2011	40	40	100	106	212	212

Maize was grown both as monoculture and intercropped with red fescue (*Festuca rubra*) sown simultaneously with maize, and Italian ryegrass (*Lolium multiforum*) sown in June. During the experiments, the maize was sown in late April following a plow, and harvested in mid-October. The CC were kept on the field until the next spring plow. In the experimental plots, the pests and diseases were carefully controlled.

2.3. The FASSET model and calibration

FASSET is a whole farm model that includes the detailed simulation of crop growth dry matter production and N content of vegetative, storage and root organs on a daily basis in response to soil, climate, crop management, water and N inputs (Berntsen et al., 2004). The baseline simulations were carried out using daily meteorological (max and min air temperatures, solar radiation, and precipitation), soil (bulk density, soil water retention, saturated hydraulic conductivity, clay, C and N content), and management data (sowing, harvesting, tillage and fertilization). While maize was sampled four times, the rest of the crops were sampled three times during the growing season and at harvest covering the period 2009 - 2011. Manevski et al. (2015) contained the detailed description on data collection and sampling. Daily climate data including maximum and minimum temperatures, precipitation, solar irradiance and reference evapotranspiration for the baseline period were obtained from the weather station of Danish Meteorological Institute located at the study site.

FASSET (version 2.5) is calibrated using a step-by-step method. First, we have run the model with default parameter values. The calibration had started with fitting the simulated soil water content to the observed value. Concurrently, the crop phenology, crop biomass, and N contents were fitted. Lastly, soil mineral N was fitted to the measured values. For the optimization of the FASSET parameters, the differential evolution algorithm for global optimization was used in R 2.1.4.1 via 'DEoptim' package (Mullen et al., 2011). In summary, several parameters were first selected to assess their sensitivity. These parameters were then tested using the sensitivity package in R 2.1.4.1 (Gilles et al., 2016). The parameters that were determined to be affecting the phenological development of maize and the CC, the biomass and N content of maize, as well as the biomass of CC, and finally the soil mineral N content were; the sum of temperatures in each crop phase, maximum radiation use efficiency, the fraction of dry-matter that present at initiation of grain filling that is translocated to grain, the fraction of net production after anthesis that goes into grain, maximum ratio between leaf area index and the dry matter of the vegetative above-ground biomass, maximum ratio between leaf area index and the nitrogen of the vegetative above-ground biomass, and the minimum soil NO_3^-. The parameters were optimized one at a time within 95% of above and below the default values. The R software then performed number of iterations until the best value for a parameter (a value that led minimum deviation of the model outputs from the observed values) was generated (Table 2). For the optimization of the phenological parameters, and the initial soil water content, no specific algorithm was used. The sum of temperatures of the each crop phase was manually adjusted to fit the simulations to the observed phenological stages. The parameter that affect the soil water content most (initial soil water content) was also manually adjusted to fit the simulated soil water content to the observed.

Because FASSET has been validated numerously using independent datasets and widely utilized in relation to the current study site (e.g. Doltra et al., 2011; Rotter et al., 2012; Doltra et al., 2015), an additional validation procedure was omitted in this study. To assess the models' simulation performance however, different statistical indexes were used. Normalized root mean square prediction error ($RMSPE_n$) was presented reflecting the accuracy of the simulated values. The closer the $RMSPE_n$ to zero, the more accurate the simulated values are (Tedeschi, 2006). $RMSPE_n$ was determined as:

Table 2
Values for selected crop parameters used in FASSET for the crops in the rotations: Ts is the sum of temperatures in each crop phase, where the subscript indicate 0 the phase from sowing to emergence; 1 from emergence to anthesis; 2 from anthesis to the end of grain filling; and 3 from the end of grain filling to ripeness; maximum radiation use efficiency (ε); the fraction of dry-matter present at initiation of grain filling that is translocated to grain (StoreForFilling); the fraction of net production after anthesis that goes into grain (FillFactor); maximum ratio between leaf area index and dry matter of the vegetative above-ground biomass (LAI_DM); maximum ratio between leaf area index and nitrogen of the vegetative above-ground biomass (LAI_N); and minimum concentration of nitrate-N left in soil water (MinSoilN).

Parameter	Units	Maize	Red fescue	Ryegrass
Ts_0	°Cd	66	125	125
Ts_1	°Cd	575	445	300
Ts_2	°Cd	275	310	420
Ts3	°Cd	200	218	155
ε	g mJ^{-2}	3.8	3	4.5
StoreForFilling	–	0.61	0.3	0.1
FillFactor	–	0.69	0.45	0.2
LAI_DM	$m^2\ g^{-1}$	0.02	0.011	0.01
LAI_N	$m^2\ g^{-1}$	0.4	0.45	0.4
MinSoilN	$g\ l^{-1}$	10	7	7

$$\mathrm{RMSPE}_n = \frac{\sqrt{\frac{(X_i - Y_i)^2}{n}}}{SD} \tag{1}$$

Where n is the sample size, Y_i is the ith measured value, X_i is the ith predicted value and SD is the standard deviation of the measurements.

Mean bias error (MB) was used to show the systematic deviations; while a negative MB is an indication of model overestimation, a positive value is underestimation (Willmott, 1982). MB was determined as:

$$MB = \frac{\Sigma(Y_i - X_i)}{n} \tag{2}$$

Finally, the accuracy of the baseline simulations was tested by the model efficiency (ME). This measure ranges from -∞ to 1, with negative values indicating the mean of the measured values is a better estimator than the model simulations. The quality of simulations increases as the ME approaches to 1 (Nash and Sutcliffe, 1970). ME was determined as:

$$ME = 1 - \frac{\Sigma(X_i - Y_i)^2}{\Sigma(Y_i - \overline{Y})^2} - (inf) \leq ME \leq 1 \tag{3}$$

2.4. Sensitivity analysis and impact response surfaces

In this study, the sensitivity of maize to climate change was examined using the IRS method across ninety nine sensitivity tests covering an uncertainty space in temperature, precipitation and CO_2 (Ruane et al., 2014). The sensitivity is defined as the rate at which the simulated response variables decrease or increase with changing climate variables.

The sensitivity tests were generated using a Latin Hypercube Sampling (LHS) method (Mckay et al., 2000), which is a type of stratified sampling method, that works by controlling the way that random samples are generated for a probability distribution. The sensitivity test included altered temperature, precipitation and CO_2. The samplings in temperature, precipitation and CO_2 were performed within a specified range (Table 3) that extended the climate change projected by global circulation models (van der Linden and Mitchell, 2009). The baseline weather data (Fig. 1) was used for all the perturbations of temperature and precipitation. The sensitivity tests were designed to present the simulation of year 2010, the mid-year in the experiments, in response to perturbed weather parameters.

IRSs were generated from matrix data that were based on every precipitation and temperature combinations that had been sampled; for a weather file in which the daily temperature is perturbed (ΔT), there are 99 weather files in which the daily precipitation was perturbed (percent P-change), so the final number of climate files that were used to generate the level plots was 9801 (99 ΔT x 99 P-change). All the perturbations were performed at a fixed rate. For example, a climate file in which the daily temperature was increased 1 °C, the daily precipitation was changed by 99 different precipitation combinations throughout the baseline period within the range as shown in the Table 3. The changes in CO_2 concentration was however, applied randomly to each 99 climate files; for every file the temperature changed, the precipitation was changed 99 times. In these 99 files, the CO_2 concentration remained the same. Because it is not possible to accurately determine the CO_2 concentration in the atmosphere in relation to a given temperature and precipitation combination. The responses that were presented in the plots (e.g. yield, N leaching etc.) were shown by changing colors with respect to variations in annual temperature and precipitation on a plot surface. The IRSs were generated using the R open source statistical software version 2.1.4.1 with the package *lattice* (Deepayan, 2008).

The effect of the elevated CO_2 was not considered in the sensitivity test of maize because the potential physiological effect of elevated CO_2 on a C_4 plant is beyond the scope of FASSET model. The effect of CO_2 on the undersown grass was accounted for, because its photosynthetic carbon assimilation rate and the stomatal conductance changed in response to the CO_2 concentrations in the following way: daily calculated dry matter is multiplied by $e^{0.4537 - \frac{170.97}{CO_{2ppm}}}$. This relationship between CO_2 concentration and dry matter accumulation was validated using FACE experiments (Olesen et al., 2002). While increasing the biomass through increased CO_2, the model also assumed that higher CO_2 concentrations reduce the transpiration rates as shown by Leakey et al. (2009).

In this study, we focused on the sensitivity of maize yield, maize N uptake, Soil Mineral Nitrogen (SMN), and NO_3^- leaching to climate change. The surface plots included the reference lines to the 2010 temperature and precipitation averages, because the experimental year 2010 was presented in this study. The color scale that represents a response (maize yield, maize N uptake, SMN, and NO_3^- leaching) to climate change varies with the perturbed weather variables, and allows comparing the results with respect to the 2010 weather. The IRS plots allow examining the temperature and precipitation combination at which the highest/lowest yield, N uptake, etc. were estimated.

Table 3
Temperature, precipitation, and CO_2 ranges relative to the baseline tested in climate sensitivity simulations.

Climate Metric	Lower Bound	Upper Bound
Temperature change (ΔT) from the baseline	−1 °C	+8 °C
Precipitation change (P-change) from the baseline	−50%	+50%
CO_2 change from the baseline (390 ppm)	−60 ppm	+508 ppm

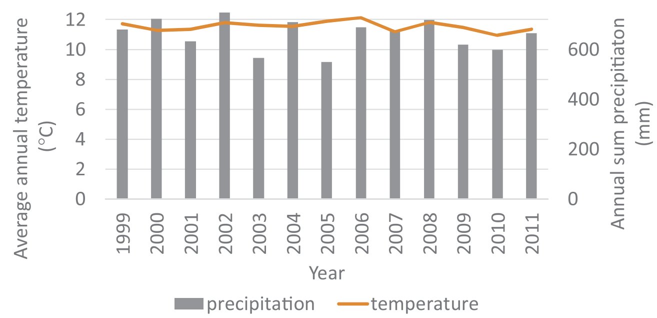

Fig. 1. The annual average temperature and precipitation in the study area from 1999 to 2011. The data obtained by the meteorological station located at the experiment site.

Table 4
The baseline performance of FASSET using normalized root mean square prediction error ($RMSPE_n$), model efficiency (ME), and mean bias (MB) between simulated* and measured crop - soil outputs. $RMSPE_n$ reflects the accuracy of the simulated values. The closer the $RMSPE_n$ to zero, the more accurate the simulated values are. MB is to show the systematic deviations; while a negative MB is an indication of model overestimation, a positive value is underestimation. ME is the accuracy of the baseline ranging from -∞ to 1, with negative values indicating the mean of the measured values is a better estimator than the model simulations.

	$RMSPE_e$	ME	MB
Yield	0.506	0.999	0.148
Grain N	0.906	0.943	1.366
Above – ground N	0.583	0.749	3.506
Soil mineral N	1.280	0.794	−18.595
Catch crops' biomass	0.319	0.999	−0.040

* Average of 2009–2010 or 2009–2011 as explained by the superscripts in Table 5.

3. Results

3.1. Baseline simulations

The FASSET model simulated the treatment effects on maize growth satisfactory including three different N input levels with and without CC, while accounting for a 10-year cropping history. The models' predictive ability was always better than the mean of observed values (Table 4, ME values). While the maize yield, grain N, aboveground N were well simulated, SMN simulation was poor, and overestimated (Table 4, MB value). At 0.5 N and 1.5 N when there was no CC, the SMN estimations were acceptable (Table 5). At 1 N however, the estimation was higher than the observed. With CC, the SMN estimations did not improve. Nonetheless, FASSET captured some variation in SMN during both the presence of ryegrass and the absence of the CC in the field. Finally, the biomass of both catch crops under different N inputs were accurately simulated (Tables 6 and 4, ME values).

Table 6
Observed (Obs) and simulated (Sim) catch crop above ground biomass (t ha^{-1}) measured in August 2009 and 2010 across three different N inputs.

	Ryegrass Obs	Sim	Red fescue Obs	Sim
0.5 N	0.82	0.81	0.39	0.37
N	0.71	0.82	0.37	0.40
1.5 N	0.60	0.69	0.35	0.38

3.2. Sensitivity of maize yield to climate change

The sensitivity tests revealed that the optimum annual temperature to achieve the highest yields in Denmark is higher than the 2010 average (Fig. 2A–C). It is however, not possible to point a specific optimum temperature, because maize yield displayed varying levels of sensitivities to the changes in temperature and precipitation depending on the amount of N input or whether there is CC in the system. The CC species itself further affected the yield response (Fig. 2B,C). Within the range of changes that were tested, the Fig. 2A–C also revealed that the maize yield was not as sensitive to precipitation as it was to temperature. The increase or the decrease in precipitation did not seem to affect the yield greatly except under 1.5 N and no CC treatment.

In general, when there was CC in the system, the maize yield became more sensitive to precipitation. Further, CC somewhat stabilized the yield across all the N treatments, especially the ryegrass; increasing or decreasing the N input did not affect the yield when ryegrass was sown as CC. Without CC, the maize yield became more sensitive to climate change and showed unstable behavior with 1.5 N application (Fig. 2A).

3.3. Sensitivity of maize N uptake to climate change

The tests showed that the 2010 yearly average temperature is higher than the values at which max maize N uptake could occur. The higher the temperature gets, the lower the N uptake became throughout all the treatments. Our tests included the temperature range -1 and +8 °C of the baseline, and the highest uptake was simulated to be always at the baseline minus 1 °C. The annual precipitation, although interacting with CC and N applications, did not seem as influential as temperature

Table 5
Observed (2009–2011) and simulated means and standard deviations (sd) of maize yield, grain N, aboveground N, mineral N in the soil across three N inputs and CC treatment. Because the cropping history are the same for all the treatments that were not included in the table.

Treatment	Yield[a] (t ha^{-1}) Obs	Sim	Grain N[a] (kg N ha^{-1}) Obs	Sim	Above-ground N[a] (kg N ha^{-1}) Obs	Sim	Soil mineral N[b,c] (kg N ha^{-1}) Obs	Sim
−CC								
0.5 N (mean) (±sd)	5.4 (0.5)	5.4 (0.7)	75 (1.5)	75.5 (2.8)	172 (17.3)	180.1 (17.5)	50.3 (17.4)	60.2 (20.2)
1 N (mean) (±sd)	4.6 (0.4)	4.2 (0.6)	74 (1.4)	73.1 (2.8)	188 (14.8)	187.5 (16.5)	70.8 (18)	95.9 (22.9)
1.5 N (mean) (±sd)	5.5 (0.4)	5.5 (0.6)	72 (1.4)	78.9 (2.5)	207 (15)	213.5 (18.4)	104.7 (25.2)	118.2 (28.4)
+Ryegrass								
0.5 N	4.4 (0.2)	4.6 (0.1)	72 (4.2)	68.1 (2)	172 (19)	168.2 (10)	57.9 (25)	73.7 (12.8)
1 N	4.8 (0.3)	4.4 (0.2)	75 (3.4)	69.6 (1.8)	189 (18)	178.2 (8.8)	70.1 (19.6)	89.5 (11.7)
1.5 N	4.7 (0.8)	4.5 (0.3)	80 (5)	72 (2.8)	210 (15)	188.8 (6)	106.1 (20.4)	96.2 (16.5)
+Red fescue								
0.5 N	5.6 (0.6)	5.1 (0.5)	85 (3.6)	81.4 (2.4)	162 (19.4)	167.2 (13)	48.1 (16.3)	66.1 (22.9)
1 N	4.7 (0.3)	4.9 (0.5)	78 (3.5)	78.9 (1.8)	191 (18.6)	182.2 (15)	60.4 (19.8)	109.9 (24)
1.5 N	6.0 (0.4)	5.8 (0.4)	83 (6)	83.7 (4.5)	199 (19)	193.1 (6.4)	80.4 (18)	86.3 (15.5)

[a] Average of 2009 and 2010.
[b] With ryegrass; average of measurements in late October and November of 2009, 2010, and two measurements in mid and late November 2011.
[c] With red fescue and no CC; average of measurements in late October and November of 2009, and a measurement in mid-March 2010.

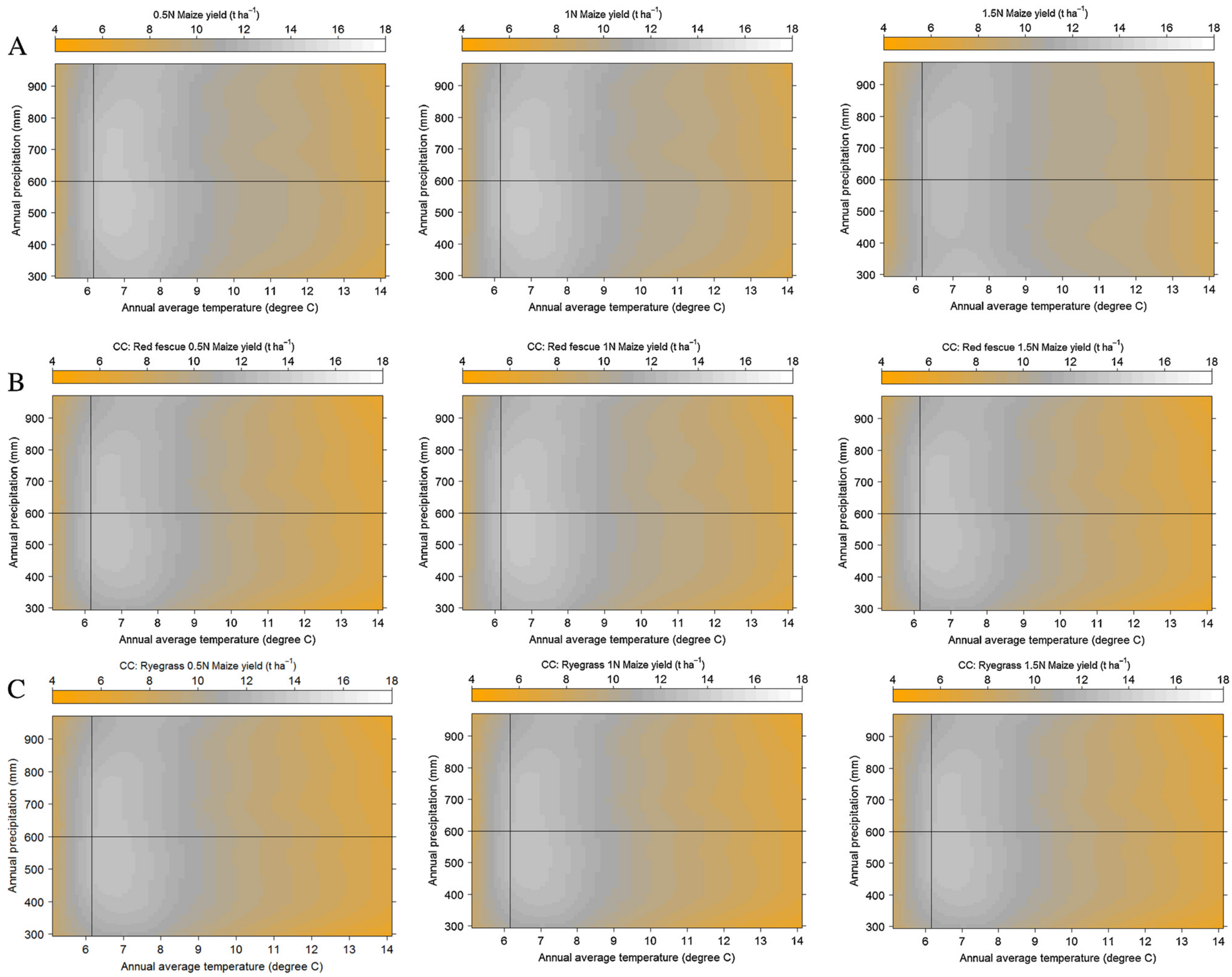

Fig. 2. Yield response in relation to climate change with and without CC, and at varying N inputs at N, 0.5 N, and 1.5 N. The yield change is indicated by the color scale bar on the top of the plots. The vertical axis is the annual precipitation in mm, the horizontal axis is the annual average temperature in °C. The horizontal and vertical black lines indicate the 2010 annual precipitation, and average temperature respectively. **A)** Yield response in three N inputs without CC, **B)** Yield response in three N inputs with red fescue as CC, **C)** Yield response in three N inputs with ryegrass as CC. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

on N uptake. Within the tested range of ± 50% of baseline average, the changes in precipitation did not affect the N uptake as such, the changes in temperature from baseline average affected N uptake greatly (Fig. 3A–C), indicating its sensitivity towards temperature variation.

The CC and N treatments had effect on the N uptake only below 8 °C annual average temperature. However, when there was no CC in the system, N uptake was not estimated to increase with increasing N input. Further, the N application had affected the N uptake inversely with increasing temperature. Without CC, the maize N uptake was more sensitive to the precipitation change than with the undersown CC treatment. The annual precipitation exceeding the observed 2010 average (599 mm) first affected the N uptake slightly positively, then negatively at and above 800 mm (Fig. 3A).

While the highest maize N uptakes were simulated to occur with ryegrass (at 0.5 N and 1.5 N applications) until 8 °C, the sensitivity of N uptake to temperature decreased with red fescue. For example, at 1 N applications and 8 °C, the N uptake was sharply reduced in the treatment where ryegrass was used, while it continued to be approximately at the same rate as 5 °C with red fescue.

3.4. Sensitivity of SMN at maize harvest

The SMN was correlated with the amount of N applied and the temperature at both the presence and the absence of the CC. At maize harvest, the amount of SMN in the soil with and without CC was different. The estimated SMN was higher when there was CC in the system, and the highest SMN was always estimated when ryegrass was sown as CC, regardless of N input and the temperature and precipitation ranges (Fig. 4C).

The sensitivity of SMN to climate change varied with the N input and the CC used in the rotation and characterized by a rather complex response. For example, at 1.5 N input, in a treatment where there was no CC (Fig. 4A-1.5 N), SMN seemed to be more sensitive to the changes in temperature and precipitation. When there is CC, the sensitivity was more localized within a specific range of temperature and precipitation. SMN was estimated to first decrease, then increase with increasing temperature when both the annual precipitation is lower and higher than 2010 average. For example, with both CC treatments, the SMN at a 500 mm annual precipitation started decreasing from 5 °C yearly average temperature until approximately 9–10 °C depending on the CC, then as the temperature continued increase SMN gradually increased (Fig. 4B,C). However, when the annual precipitation is near the 2010 average at 599 mm, the decrease in SMN as the temperature increase from 5 C, and increase at higher temperatures was not as fast as when the precipitation was at 500 mm.

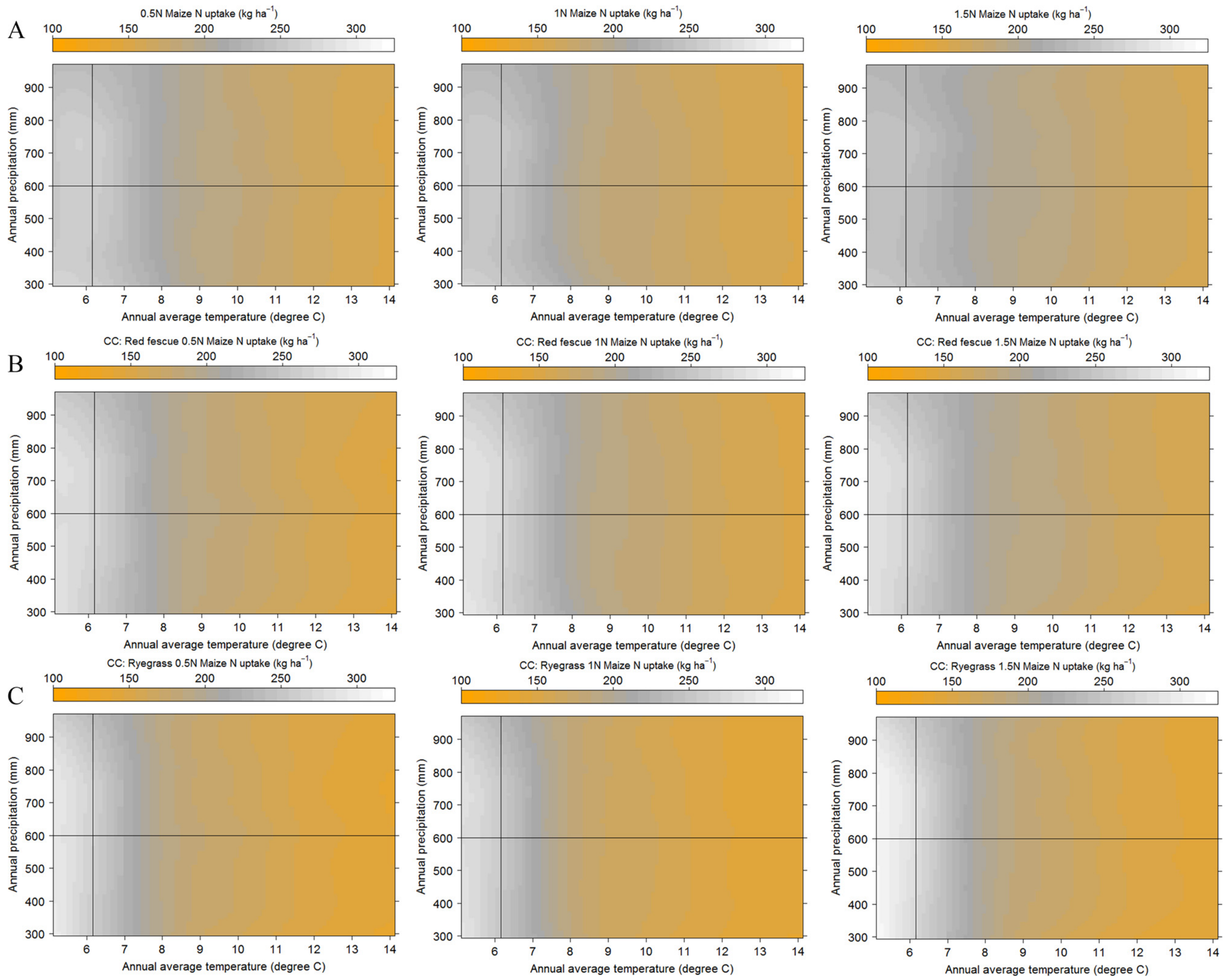

Fig. 3. Maize N-uptake response in relation to climate change with and without CC, and at varying N inputs at N, 0.5 N, and 1.5 N. The change in the uptake is presented by the color scale bar on the top of the plots. The vertical axis is the annual precipitation in mm, the horizontal axis is the annual average temperature in °C. The horizontal and vertical black lines indicate the 2010 annual precipitation, and average temperature respectively. **A)** N-uptake response in three N inputs without CC, **B)** N-uptake response in three N inputs with red fescue as CC, **C)** N-uptake response in three N inputs with ryegrass as CC. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.5. *Sensitivity of NO_3^- leaching*

The climate variables and the varying N treatment substantially affected, and interacted with the NO_3^- leaching. In general, while the increasing temperature steadily increased the NO_3^- leaching, increases in precipitation were found to either increase or decrease the leaching depending on the temperature. A certain lower bound of precipitation (≈300 mm annually) determined whether leaching had occurred at all without using CC (Fig. 5A). The tests indicated that the CCs had considerable influence on NO_3^- leaching especially at 0.5 N input (Fig. 5A vs. B and C). Both CC increased the leaching at all N input levels. The estimated NO_3^- leaching was always lowest and less sensitive to temperature without CC.

At 0.5 N, the leaching was highest with the ryegrass (Fig. 5C-0.5 N), however in all the other N inputs, the leaching was higher with the red fescue. In CC treatments, and at approximately 9 °C annual average temperature, the leaching increased sharply. At the average yearly temperature around 9 and 12 °C, the leaching decreased and increased as the annual precipitation exceeded 2010 average (599 mm), whereas with no CC treatments, the higher annual precipitation than 2010 average caused constant fluctuation in leaching between 10 and 12 °C until the maximum precipitation level that was tested (Fig. 5B-C), except at 0.5 N level.

4. Discussion

4.1. *Maize response to climate change*

The baseline performance of the simulations of the maize phenological parameters was generally satisfactory. The biomass yield of the CC was also well correlated with the observations in all the N treatments (Table 6). Accurate CC biomass simulation was particularly important in studying the effect of CC on N availability for the subsequent crop. Given the baseline simulation performance, the sensitivity tests hence allowed us explore the detailed maize crop responses to climate change.

It was estimated that the effect of moderate warming on maize yield in Denmark from 6 to 7 °C in annual mean temperature is positive, while the effect of higher temperatures was strongly negative regardless of increased or decreased precipitation, N input, and the use of CC in the cropping system. The increasing temperatures combined with decreasing precipitation affects maize growth negatively, especially the reproductive stage when maize is most sensitive to drought stress (Cairns et al., 2012). Using multiple CMIP5 (Coupled Model

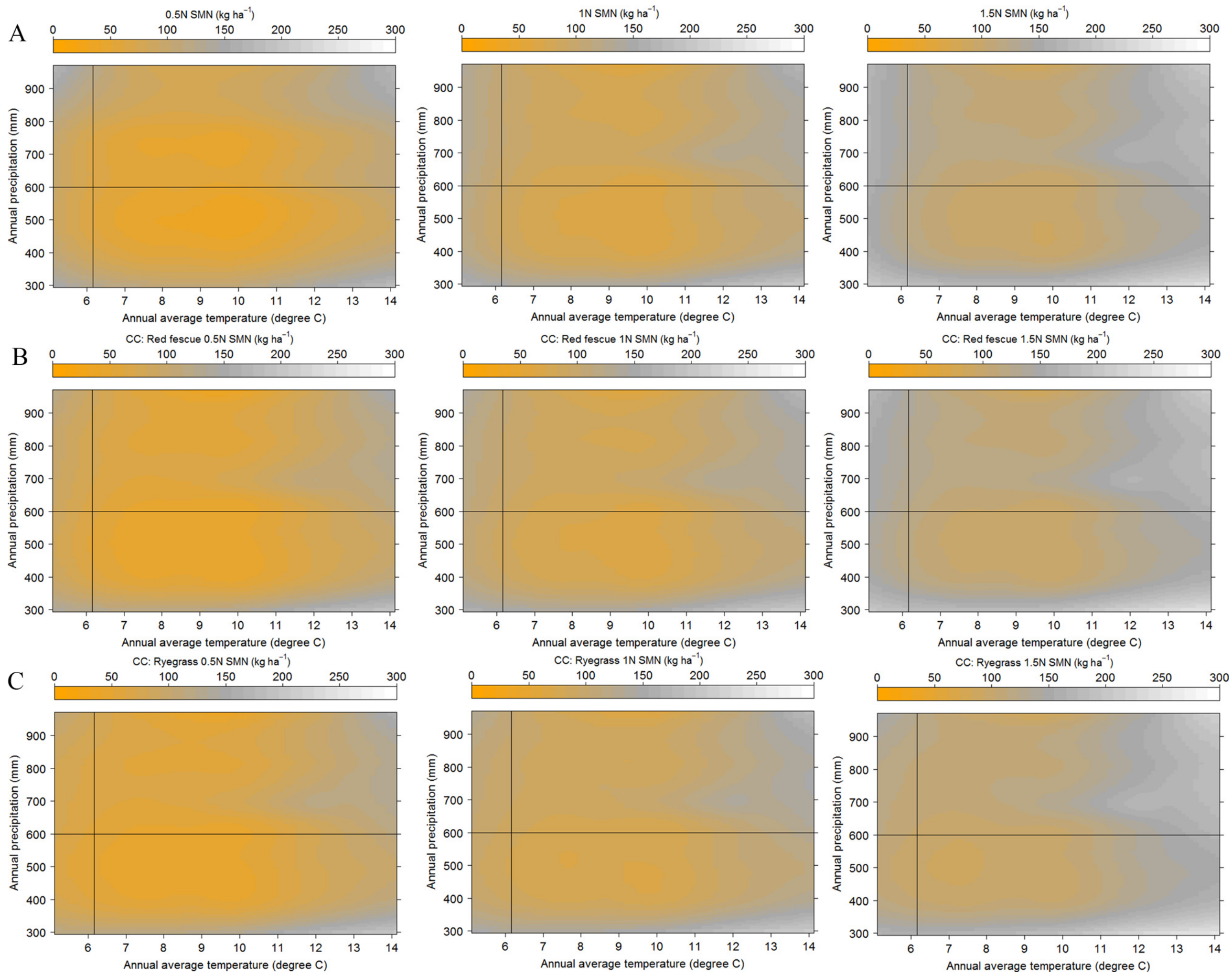

Fig. 4. The soil mineral N (SMN) response in relation to climate change with and without CC, and at varying N inputs at N, 0.5 N, and 1.5 N. The change in the SMN is presented by the color scale bar on the top of the plots. The vertical axis is the annual precipitation in mm, the horizontal axis is the annual average temperature in °C. The horizontal and vertical black lines indicate the 2010 annual precipitation, and average temperature respectively. **A)** SMN response in three N inputs without CC, **B)** SMN response in three N inputs with red fescue as CC, **C)** SMN response in three N inputs with ryegrass as CC. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Intercomparison Project Phase 5) climate models and scenarios, Ummenhofer et al. (2015) assessed historical and future climatic conditions and their effect on maize yield in Iowa, USA. The years that were estimated with extreme high and low yield were associated with increased or sustained levels of summer (June-Sept) precipitation, and decreased summer precipitation respectively in the region. However, they reported substantial variability between climate models in the projection of extreme years both historically and in the future in determining the effect of precipitation and temperature on maize yield. Their study did not indicate a significant interactive effect of precipitation and temperature on maize yield either.

The annual precipitation range that was tested in our study was between 300 and 950 mm. Considering the irrigation requirement of maize for optimal growth; 500–800 mm, the FASSET model did not estimate any yield sensitivity towards annual precipitation rates at between approx. 400 and 800 mm. However, the sensitivity of the crops towards short term climatic changes is an important parameter to be taken into account in relation to the impact studies of climate change. The lack of sensitivity of maize yield towards precipitation might be explained by the fact that this study did not account for the seasonal distribution of the precipitation, but the annual cumulative precipitation. With CC however, the sensitivity of maize yield to precipitation change is increased due likely to CC's water use. Red fescue, in comparison to ryegrass, did not increase the sensitivity of the yield to precipitation change as much as ryegrass did.

The increased N input from 0.5 N to 1 N marginally increased the yield under climate change, and further increase in N input was not beneficial for the maize yield at all. The yield reduction in higher temperatures is explained by the accelerated phenology that was projected by FASSET, especially the flowering in response to temperature that occurred in as early as mid-June as opposed to mid-August (data not shown). This is because the effect of increased temperature on crops is represented by the reduced growth period in FASSET. In addition, the climate sensitivity tests were carried out without applying adaptive measures to amend the impact of higher temperatures, such as climate adjusted sowing dates, or assumption of different maize cultivars. Using current maize cultivars, the tests provide an estimate of the upper temperature boundary at which a sharp decrease in silage-maize yield in Denmark may occur under both well-watered and drought conditions. In their meta-analysis, Iizumi et al. (2017) also reported that the yield growth of maize in countries located at mid and high latitudes will stagnate in response to 1.5 °C increase in temperature from 1958 to 2013 average due to the limited effect of elevated CO_2 (fertilization) on maize. The point at which the fertilization effect of C_4 crops becomes insufficient to compensate for yield decline associated with decreased crop durations under warmer conditions.

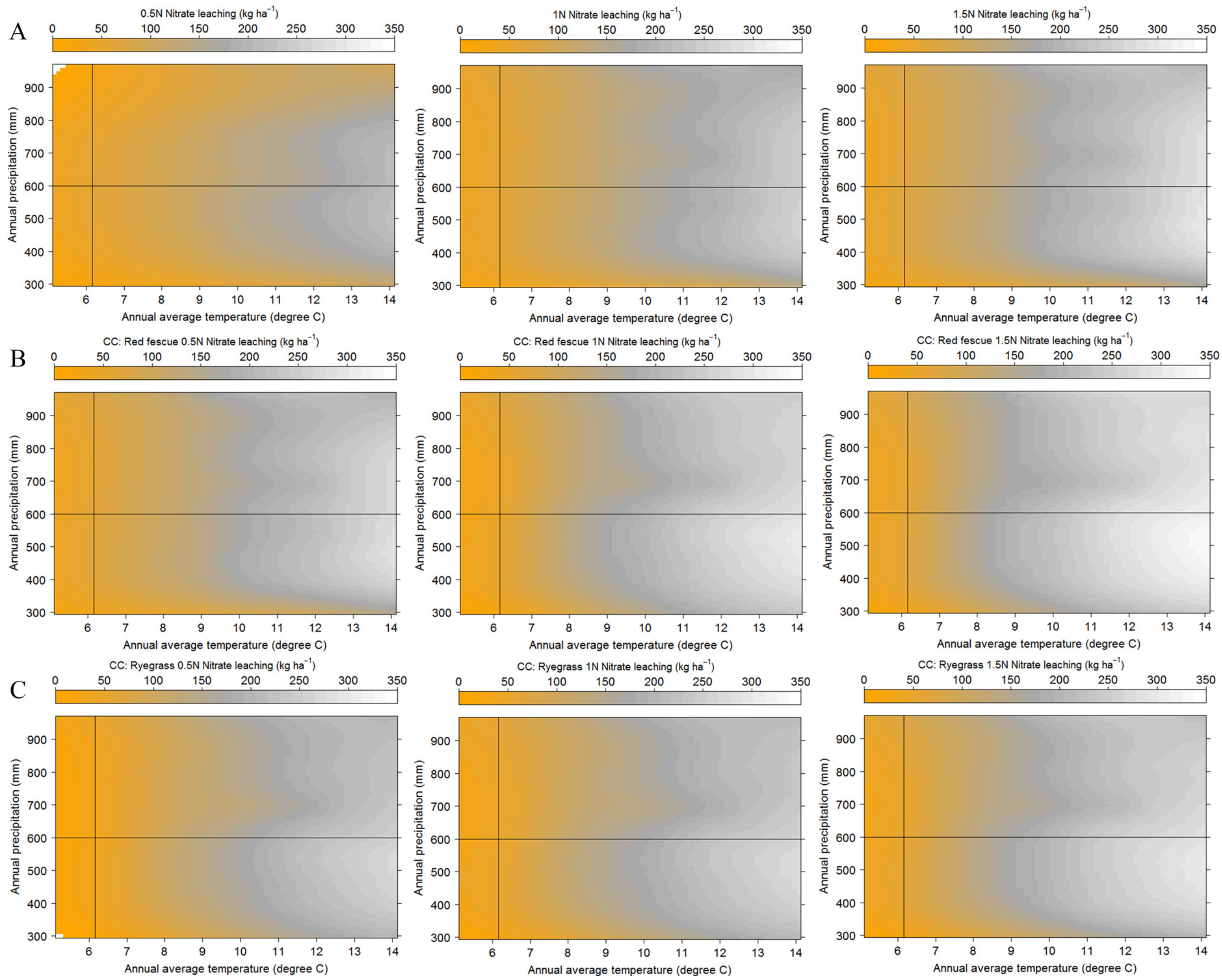

Fig. 5. Nitrate leaching response in relation to climate change with and without CC, and at varying N inputs at N, 0.5 N, and 1.5 N. The change in the nitrate leaching is presented by the color scale bar on the top of the plots. The vertical axis is the annual precipitation in mm, the horizontal axis is the annual average temperature in °C. The horizontal and vertical black lines indicate the 2010 annual precipitation, and average temperature respectively. **A)** Nitrate leaching response in three N inputs without CC, **B)** Nitrate leaching response in three N inputs with red fescue as CC, **C)** SMN response in three N inputs with ryegrass as CC. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The hybrid maize cultivars with delayed maturity may show a less reduction in yield as demonstrated by Tao et al. (2016), and further resilience might be anticipated considering the contribution from increased water use efficiency via the effect of elevated CO_2 on transpiration (Kaur et al., 2012). The tests with adaptive cultivars are therefore needed to answer the question as to what extent the yield variation is contributed by the accelerated growth period compared to the other direct effects of temperature on maize physiology.

One of the most important aspects of the crop physiology is the N uptake from soil and the way in which it is affected by the climate change. The bulk of maize N uptake occurs quick, and relatively late in the season in Northern Europe; by flowering, maize has taken up approximately 63% of its N requirement, while the rest is taken up during the grain filling (Ciampitti and Vyn, 2012). This physiological behavior is suitable for the uptake of soil N that has been mineralized in summer. In the simulation of the current experiments, N uptake (up to 8 °C) and the amount of SMN were correlated with the use of CC. While the SMN increased with increasing temperature and N input, N uptake by maize sharply decreased with increasing temperature (above 8 °C annual average), and did not change, or marginally increased with increasing N input. These results emphasized that the additional N whether from increased mineralization due to warmer climate, or increased direct N input is not beneficial for the maize crop. The CCs in the system do indeed surge the N uptake potential of maize (Fig. 3A–C) until 8 °C of annual average temperature.

The current study suggested that, by the time of maize harvest in October, the SMN was always higher with CC treatments compared to non-CC treatments under wide range of temperature and precipitation conditions. The increased SMN in autumn is often linked to silage maize in the fields with manure applications (Kayser et al., 2011), which moves down the soil profile causing NO_3^- leaching. Higher SMN in our simulations is fundamentally related to the higher mineralization of N than its immobilization during the decomposition of the CC residues in FASSET affected by temperature. However, it is not possible to conclude the overall SMN estimations suggested by FASSET are realistic. In simulating the SMN, we speculated that the calculation of warming effects on organic matter decomposition was probably the main source of the poor performance. Smith et al. (2008) suggested that temperature sensitivity on organic matter decomposition changes according to soil pools. In FASSET, the effect of temperature on decomposition rate is identical in all its seven different soil pools. The secondary source of the poor performance might be the fact that FASSET has fixed C/N ratios in its soil microbial pools as well, so dynamic simulation of the microbial activity can never be achieved. Thirdly, the number of initially selected

parameters that were to be optimized might not have been sufficient for the model to be performed well in estimation of SMN. Despite the clear aims and consistent parameter optimization procedures, the choice of which parameters to include in the optimization remains distinctly subjective, and might have led to poor SMN simulation performance.

The relationship between shoot N assimilation of a crop and increased CO_2 concentration is not mechanistically defined in FASSET (Bloom et al., 2010). This is of great importance regarding C_3 (catch) crops (Bloom et al., 2014). Currently though, none of the crop-soil models that are being used globally incorporated the latest knowledge on differential N assimilation of C_3 plants, and the way in which the assimilation is affected by the elevated CO_2 concentrations.

The use of CC is frequently regarded to be beneficial for the reduction of NO_3^- leaching (Thorup-Kristensen et al., 2003). In various studies from northern Germany, the Netherlands, Denmark and Sweden the beneficial effect of CC on N leaching was documented (Wachendorf et al., 2006; Decrem et al., 2007; Askegaard et al., 2011; Schroder et al., 2013; Manevski et al., 2015). Yet there are other studies from Sweden and Denmark that reported the limitations of CC in reducing N leaching (Hansen et al., 2000; Hoffmann and Johnsson, 2000). Most recently, Hansen and Eriksen (2016) found that maize production with CC using undersown grass was indeed of high risk for its potential in increasing NO_3^- leaching. The extent to which the potential for reduced leaching using CC distinctly depends on soil type and climatic conditions (Askegaard et al., 2005). Our study suggested that the warming of the climate along with the projected increase in precipitation in Denmark will greatly challenge the management of N in maize cropping systems. In the current study, FASSET model estimated that the annual average temperature higher than 8 °C in Denmark is very critical for the NO_3^- leaching. Above 8 °C, the leaching was highly increased, and it was estimated to be insensitive towards precipitation. In the same experimental location, Patil et al. (2012) reported that an increase in winter precipitation had less impact on N leaching than summer precipitation. In addition, during winter, high rates of precipitation correlated negatively with NO_3^-N concentration in two cereal cropping systems which were associated with the non-significant effect of precipitation on NO_3^- leaching. It was also found that there was no interaction between temperature and precipitation to significantly affect NO_3^- leaching, or N concentration in the leachate (Jabloun et al., 2015). We suggest that the lack of sensitivity of NO_3^- leaching to precipitation in the current study stems from the absence of data that included the seasonal distribution of the rainfall as opposed to cumulative annual rates.

The use of CC has further amplified both the amount of N that leached, and the sensitivity of leaching to temperature. This can be attributed to the SMN estimations in FASSET, which were always higher with CC than without CC treatments. Red fescue was associated with the highest NO_3^- leaching at every N input. In the current study, the reliability of FASSET estimations regarding NO_3^- leaching was also indefinite, due to the intrinsic relationship between SMN and NO_3^- leaching.

Aside from management interventions consistent with the climate change such as the sowing date and/or introduction of new cultivars, reducing the amount of N input to the cropping system might be the initial measure to be implemented for a reduced leaching potential when using grass CC under warmer climate. This is mainly because we estimated 0.5 N did not affect the yield or maize N uptake considerably until 8 °C. At lower temperatures, the CC, especially the ryegrass was found to be highly favorable for maize N uptake. Ultimately however, the undersown grass in silage maize may not be a viable option in relation to warmer climate for all of its benefits were widely overshadowed by the excessive NO_3^- leaching risk. One way to address the NO_3^- leaching from maize cultivation would be to focus on increasing crop N uptake efficiency by both maize and CC. Root growth in this context is an essential feature for the N uptake efficiency as deeper roots improve the uptake from deeper soil layers and reduce NO_3^- leaching (Ramirez-Garcia et al., 2015; Thorup-Kristensen and Rasmussen, 2015). Further research on potential adaptation of different deep-rooted species under warmer climate that might be suitable as undersown CC is therefore highly needed.

All the physiological parameters that were investigated in this study are greatly prone to be affected by the extreme events (heavy rainfall, drought, severe cold, heatwaves and storms) that were expected to occur in the future more often than today (Coumou et al., 2013; Gallant et al., 2014). This study did not account for the distribution of the precipitation (e.g. sudden floods) or the temperature (e.g. heat waves) throughout a year that might haphazardly occur in the future. Nonetheless, it was demonstrated that the increase in yearly mean temperature will significantly challenge silage maize cultivation, for not only warming will result in more days at the physiological threshold beyond which the crop will be stressed, it will also affect the nutrient availability negatively.

5. Conclusions

This study employed an approach called IRS that involves using a process based model in studying the effect of climate change on the sensitivity of maize growth and associated agro-ecological responses. While the sensitivity tests do not attempt to compute a projection of silage maize yield under future climate, considering the agreement between baseline observations and the simulations of the cropping parameters, they indicated that the rising temperature will be a significant challenge for sustainable forage-maize production in Denmark.

This study suggested that the management practices in relation to silage maize production that is governed by the current climate and local conditions must change considerably by the warming climate. Without any adaptation measures and using the current levels of N inputs, the NO_3^- leaching will increase dramatically above 8 °C of annual average temperature (corresponding to a warming of ≈ 2 °C relative to the analysis year 2010). The undersown CC will lead to both increased SMN and excessive NO_3^- leaching. The yield and maize N uptake will gradually be reduced. Along with new maize cultivars that are adapted to the warmer climate in Denmark in terms of N use efficiency and phenological development rate, deep-rooted plant species might be adapted to replace the undersown grass as CC.

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